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# Critical currents at 77.3 K under magnetic fields up to 27 T for an Y-Ba-Cu-O film prepared by chemical vapor deposition

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Critical currents of an $Y_1Ba_2Cu_3O_{7-\delta}$ film prepared by a chemical vapor deposition technique have been measured resistively. Excellent critical current properties in high fields up to 27 T are obtained at 77.3 K. The value of $J_c$ is $4.1\times10^5$, $1.9\times10^5$, and $6.5\times10^4$ A/cm$^2$ at 2, 10, and 27 T, respectively. The upper critical field defined by zero resistivity is estimated to be 35 and 180 T at 77.3 and 0 K, respectively. A peak effect in the critical current is observed at high fields.

Many studies on bulk samples of high $T_c$ superconducting oxides such as Y-Ba-Cu-O,[1] Bi-Sr-Ca-Cu-O,[2] and Tl-Ba-Ca-Cu-O[3] exhibited disappointingly low transport critical current density $J_c^t$ measured resistively in magnetic fields. On the other hand, magnetization measurements on these superconducting oxides suggested higher values of $J_c$. This difference is thought to be related to the weak links at grain boundaries in superconducting oxides.[4] Recently, several epitaxially grown thin films with well-aligned grains have been prepared by techniques of chemical vapor deposition (CVD),[5] electron beam,[6] and sputtering.[7] It is expected that $J_c^t$ increases in films with well-aligned grains, because of the reduction and quality improvement of grain boundaries.

In this letter, we report significantly high $J_c^t$ in a newly prepared CVD sample of an epitaxially grown $Y_1Ba_2Cu_3O_{7-\delta}$ film up to 27 T at 77.3 K. The global pinning force $F_p = J_c \times B$ will be also discussed.

The details of the film preparation by CVD were reported in our previous paper.[5] Source materials used were $\beta$-diketonate chelates of Y, Ba, and Cu. We succeeded in preparing $Y_1Ba_2Cu_3O_{7-\delta}$ films epitaxially on $SrTiO_3$(100) single-crystal substrates at a deposition temperature as low as 850 °C. X-ray analysis confirmed a very strong $c$-axis orientation perpendicular to the substrate surface. In addition, a small intensity of $b$-axis grown perpendicular to the CVD film surface was observed. The sample dimension is about $1.8\times10$ mm$^2$ and 1 $\mu$m thick. Current and voltage terminals were attached by ultrasonic soldering.

The transition temperature $T_c$ and the upper critical field $B_{c2}$ were determined from the resistive transition, which were measured in a temperature variable cryostat in zero or constant magnetic field. In measurements of critical currents, the sample was directly immersed in the liquid nitrogen. We used a pulsed power supply and measuring system developed by Sumitomo Electric Industries, Ltd. This system consisted of a programmable current supply (20 A, 16 V) and a digital oscilloscope (sampling, 250 MS/s). Critical currents were measured at the sweep rate of 10 A/0.5 s and by the sensitivity of 5 $\mu$V/div through an isolation amplifier, and were decided by the voltage appearance. Magnetic fields were applied parallel to the film surface and perpendicular to the current by use of a hybrid magnet[8] with a 52 mm room-temperature bore at Tohoku University.

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Figure 1 shows a SEM photograph of the film surface including a fractured cross section. A very dense microstructure is observed in comparison with the previous sample[5] which was deposited at 900 °C. Moreover, one notices numerous projections like needles on the film surface. These projections might correspond to $b$-axis diffraction in the x-ray analysis mentioned before. Detailed investigations on this strange microstructure are in progress.

Figure 2 indicates the resistive transitions in 0, 21, and 25 T. $T_c$, $B_{c2}$ are determined from the extrapolation to the zero resistivity of the resistive transition. As can be seen, $T_c = 89$ K, $B_{c2}(82\text{ K}) \approx 21$ T, and $B_{c2}(81\text{ K}) \approx 25$ T, respectively. From these values, the slope of $B_{c2}$ near $T_c$ can be estimated to be about 3 T/K. From this result, the values of $B_{c2}(T)$ at 77.3 K and 0 K are estimated to be 35 and 180 T, respectively, on the basis of the BCS-GLAG theory.

Figure 3 shows critical currents of the CVD film at 77.3 K and in magnetic fields up to 27 T. While the noise level in the measurements was about 1.2 $\mu$V in the low-field region below 6 T, its level increased with increasing magnetic field, and reached about 11 $\mu$V at 27 T. In this figure, errors of critical currents caused by this noise are indicated by vertical bars. As can be seen, these $J_c^t$ properties at 77.3 K for this sample are very excellent. The critical current density values are $J_c^t = 4.1\times10^5$ A/cm$^2$ at 2.0 T, $J_c^t = 1.9\times10^5$ A/cm$^2$ at 10 T, and as high as $J_c^t = 6.5\times10^4$ A/cm$^2$ even at 27 T.

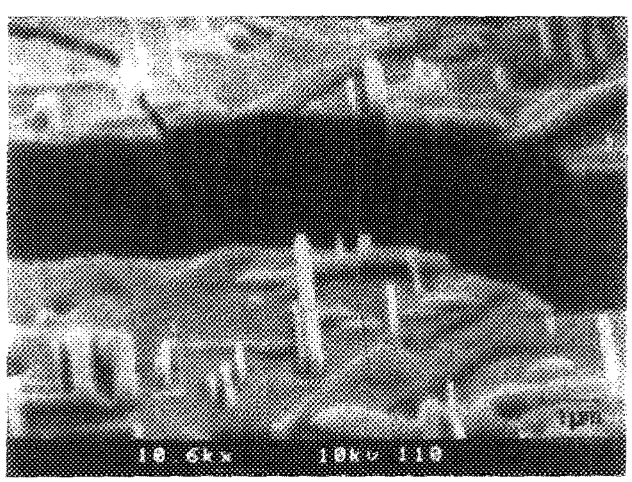

FIG. 1. Scanning electron micrograph of an epitaxially grown CVD $Y_1Ba_2Cu_3O_{7-\delta}$ film.

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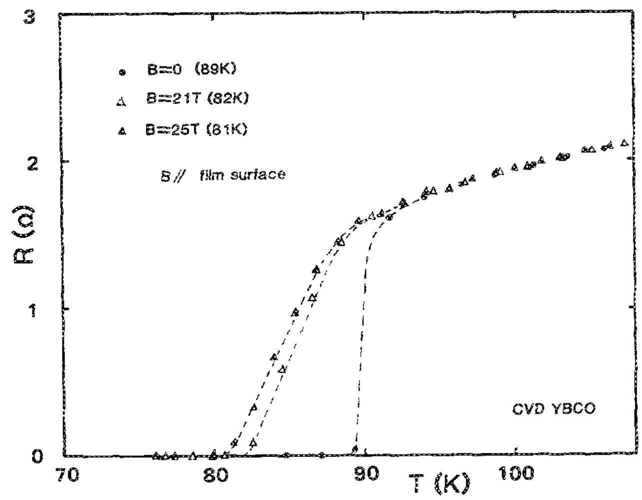


FIG. 2. Resistance vs temperature curves for the CVD Y-Ba-CuO film in $B = 0$, 21, and 25 T.

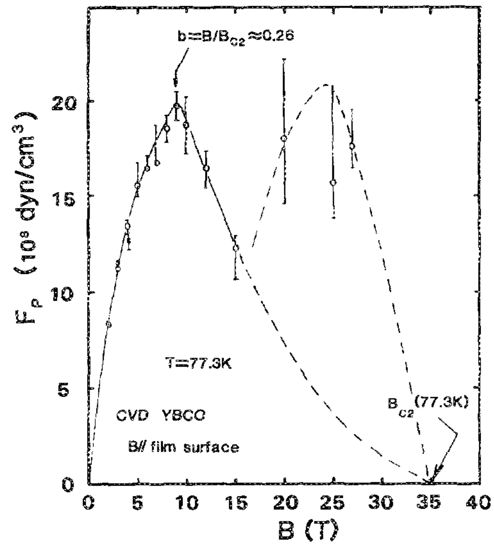


FIG. 4. Global pinning force at 77.3 K for the CVD Y-Ba-Cu-O film.

Moreover, in the high-field region more than 15 T, one should note a peak effect, which has been observed in several conventional superconductors such as NbN.[9]

Figure 4 shows the global pinning force $F_p$ evaluated from $F_p = J_c^t \times B$ at 77.3 K. We obtain a clear maximum of $F_p$ near 9 T. Since $B_{c2}$ at this temperature is 35 T, the reduced field $b = B/B_{c2}$ at the peak of $F_p$ becomes about 0.26. In addition, the peak effect in $J_c$ becomes clear in high fields more than 15 T.

The flux pinning curve except this peak effect resembles the data obtained by Kes *et al.*,[10] who measured magnetization on a single crystal of $Y_1Ba_2Cu_3O_{7-\delta}$ at 20.4 K in fields up to 38 T by use of a pulsed magnet. They estimated the critical current densities from the hysteresis of the magnetization. According to their results, the reduced field $b = 0.31$ at the peak is indicated in the single crystal.

Recently, there are important discussions on the giant flux creep in high $T_c$ superconducting oxides.[11] According to Dew-Hughes,[12] the upper limit of $J_c^t$ due to the giant flux creep is about $3 \times 10^3$ A/cm$^2$ at 80 K and 2 T. Therefore, it is supposed that there exists strong flux pinning enough to suppress the giant flux creep in our CVD film sample which shows the excellent $J_c^t$ properties as shown in Fig. 3.

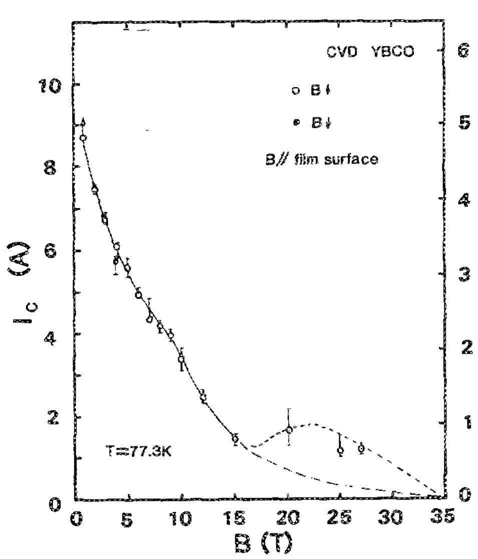


FIG. 3. Magnetic field dependence of critical currents at 77.3 K up to 27 T for the CVD Y-Ba-Cu-O film.

The peak effect in the magnetic field dependence of the critical current has been discussed in terms of the different flux pinning mechanism.[13] Physical understanding for the peak effect in the vicinity of $B_{c2}$ is not converged yet. Anyhow, we do not understand what kind of flux pinning is most effective in superconducting oxides. The excellent $J_c^t$ properties in our CVD film of $Y_1Ba_2Cu_3O_{7-\delta}$ might be associated with the strange microstructure including many projections as shown in Fig. 1.

In summary, the epitaxially grown $Y_1Ba_2Cu_3O_{7-\delta}$ film prepared by the CVD process exhibits excellent high $J_c^t$ properties at 77.3 K and in fields up to 27 T. The value of $J_c^t$ at 77.3 K is $4.1 \times 10^5$, $1.9 \times 10^5$, and $6.5 \times 10^4$ A/cm$^2$ at 2, 10, and 27 T, respectively. The upper critical field at 77.3 K is estimated to be 35 T. Moreover, we found a peak effect of $J_c^t$. This peak effect may improve the $J_c^t$ ability in the very high magnetic fields at 77.3 K.

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